

Preface

Ten years has passed since the 1986 publication of two issues of the *IBM Journal of Research and Development* reviewing the scanning tunneling microscopy (STM) technique. In the same year, two IBM Zurich Research Laboratory scientists, G. Binnig and H. Rohrer, shared the Nobel Prize in physics for their pioneering work in this field. Since then, the STM field has grown at a tremendous rate and has stimulated a range of new techniques.

The STM showed that it was possible to scan a conducting sample surface with a sharp probe tip located about a nanometer above the surface and, by adjusting the tip-surface distance to maintain a constant current, produce three-dimensional images having atomic-scale resolution. To achieve this resolution, the STM has relied on piezoelectric drives and feedback electronics for scanning and for controlling the vertical motion of the probe tip. Besides atomic imaging, a scanning tunneling spectroscopic (STS) version of the STM has been used to characterize the electron density of states of surfaces from measurements of the voltage dependence of the tunneling current at tip-to-surface distances of about one angstrom. STM has enabled the measurement of a variety of phenomena such as luminescence, nonlinear optical mixing, and the probing of Schottky barriers with ballistic electron emission. In addition, the STM has been used for surface modification, a supreme example of which is the writing of patterns and structures on crystal surfaces by moving single xenon atoms. The STM has also been used to perform localized electrochemistry and to selectively modify surfaces by using the high electric fields available at the probe tip to deposit or remove material.

In parallel with these accomplishments and novel studies of conductive surfaces achieved during the early STM years, Binnig, Quate (Stanford), and Gerber (IBM) developed the atomic force microscope (AFM) in 1986. This instrument operated on a principle different from the STM—it measured the repulsive force interaction between the electron clouds on the probe tip atoms and those on the sample surface atoms—and opened a path to imaging both insulating and conducting surfaces with atomic resolution. The frictional force microscope, a variation of the AFM, measures the lateral force of atomic interactions as the probe traverses the surface. As AFM technology matured, the force sensitivity increased by several orders of magnitude. The higher sensitivity of attractive-mode or noncontact AFM gave rise to new forms of nanometer-scale microscopies, including magnetic force microscopy (MFM) for imaging magnetic properties and kelvin probe (KPFM) and electrostatic force microscopy (EFM) for imaging charge and surface potentials. Magnetic resonance force microscopy (MRFM) extended the MFM concept to measure nuclear spins—with the eventual possibility, given

sufficient improvement in force sensitivity, of detecting the nuclear spin of a single atom.

Other forms of scanning probe microscopes—those that do not depend on tunneling or forces between a probe tip and a sample surface—have also been demonstrated. Examples include the scanning thermal microscope, which responds to local thermal properties of surfaces, the scanning capacitance microscope for dopant profiling, and the near-field optical microscope. More recently, the scanning SQUID microscope with a spatial resolution of 10 micrometers has been used to observe half-integer flux quanta, and the femtosecond field-emission camera has been used to detect the motion of individual atoms and molecules.

Scanning probe microscopy has found practical application as well. Noncontact AFM for metrology has moved into manufacturing lines. MFM and the scanning capacitance microscope have become tools of development laboratories. Although commercial products have yet to be realized, they are on the horizon. Data storage is an important area of product exploration: The storage and retrieval of information on a 10-nm scale has been demonstrated using scanning probe techniques. Although the achievable data rates do not satisfy present requirements, they are improving; recent demonstrations with near-field optics have brought them much closer to acceptable values.

In summary, the underlying principle of the STM has provided impetus for the development by many investigators of various related techniques. These techniques utilize the piezoelectric scanning and feedback principles of the STM, but they form images by monitoring a variety of local interactions other than the tunnel current. We have briefly described the evolution of the STM into what can now be generically termed scanning (or proximal) probe microscopy, which has occurred since the first STM-related issues of this *Journal*. The papers in the present issue describe recent progress by IBM researchers in a number of these new techniques.

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Guest Editors